THE 12×32 POP-UP BOLOMETER ARRAY FOR THE SHARC II CAMERA

C. Darren Dowell, Jeffrey E. Groseth, Thomas G. Phillips
California Institute of Technology, 1200 E. California, Pasadena, CA 91125

Christine A. Allen, Sachidananda R. Babu, Murzy D. Jhabvala, S. Harvey Moseley, Jr., & George M. Voellmer
NASA-Goddard Space Flight Center, Greenbelt, MD 20771

ABSTRACT

SHARC II is a 350 μm facility camera for the Caltech Submillimeter Observatory (CSO) expected to come on-line in 2002. The key component of SHARC II is a 12×32 array of doped silicon "pop-up" bolometers developed at NASA/Goddard and delivered to Caltech in March 2002. Each pixel is 1 mm × 1 mm, coated with a 400 Ω/square bismuth film, and located λ/4 above a reflective backshort to maximize radiation absorption. The pixels cover the focal plane with >95% filling factor. Each doped thermistor occupies nearly the full area of the pixel to minimize 1/f noise. We report some results from the first cold measurements of this array. The bolometers were located inside a dark cover, and 4×32 pixels were read simultaneously. In the best 25% of winter nights on Mauna Kea, SHARC II is expected to have an NEFD at 350 μm of 1 Jy $s^{1/2}$ or better.

BOLOMETER ARRAY DESIGN AND READOUT ELECTRONICS

The 12×32 bolometer array for SHARC II was completed in March 2002. In addition to fulfilling the need for a larger format CSO camera, the SHARC II array also serves as a prototype for the array to be constructed for HAWC on SOFIA[1].

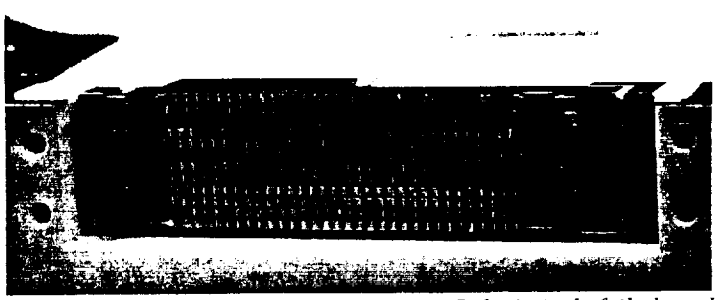


Figure 1: *Focal plane of 12×32 SHARC II bolometer array. Only 4 pixels failed mechanically.*

Pop-up arrays are built by first manufacturing flat 1×32 rows of bolometers on silicon wafers via photolithography and micromachining[2]. Each row is folded over the edge of a thin ceramic bus bar to hide the electrical leads behind the focal plane. The pixels (1 mm × 1 mm) and thermally-isolating legs (4 each 16 μm wide × 420 μm long) are patterned from 1 μm thick silicon membrane, and the folds produce 90 degree twists in the legs. Many rows – 12 in this case – are stacked to produce a two-dimensional array with >95% areal filling factor (Figure 1). To optimize the ~400 μm performance of SHARC II, a 400 Ω/square absorbing film was evaporated on the bolometers, and the gold-plated edge of each bus bar was located 100±10 μm behind the bolometers, producing a theoretical radiation absorption efficiency of >90%.

Contact information for C. Darren Dowell: email: cdd@submm.caltech.edu, phone: 626 395-6675

The bolometer array is cooled by a ^{3}He refrigerator to 0.3 K and is supported from a 4 K housing by a kinematic Kevlar suspension. The 768 leads from the bolometers cross this temperature interface via micromachined polyimide bridge wires onto which a metal film has been evaporated. Each wire is approximately 20 μm × 2 μm × 3 mm long. The 4 K housing also contains connectors and slots for 3 readout drawers and incorporates multiple heat sinks and radiation shields to prevent the 90 mW readout power from affecting the bolometer performance (Figure 2).

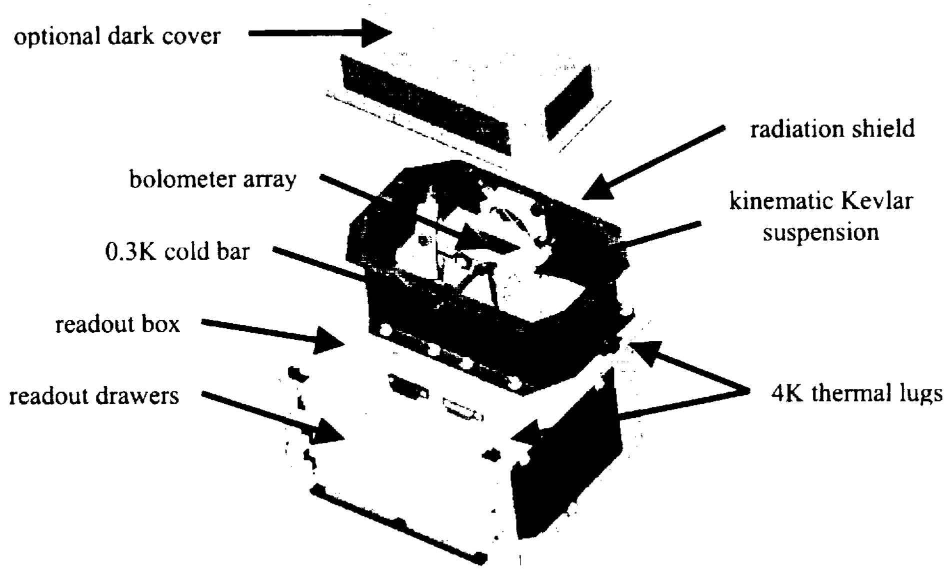
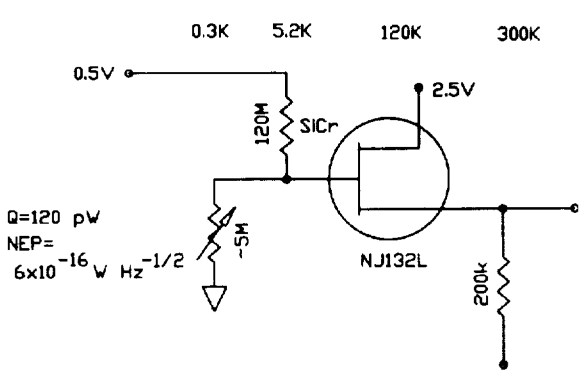


Figure 2: Mechanical overview of SHARC II detector.

Each readout drawer contains 128 SiCr load resistors and 128 JFETs to service a 4×32 section of the bolometer array. The load resistances are sufficiently large so that their Johnson noise is only a minor contributor to the total system noise, despite being relatively warm (Figure 3). The JFETs are located on a ceramic island thermally isolated with Vespel tubes and electrically accessed via polyimide bridge wires.



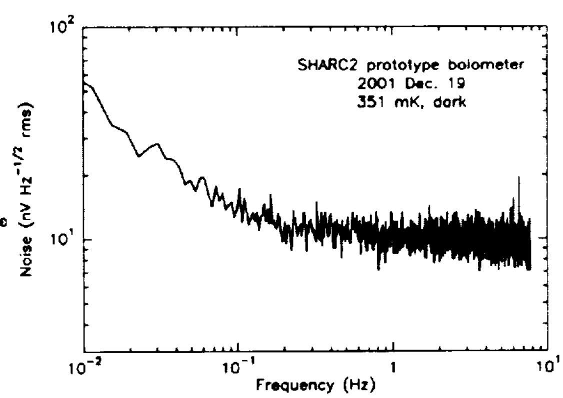


***Figure 3 (left):** Basic readout circuit for SHARC II pixels. Under the radiation load of 120 pW, the pixel warms considerably above the base temperature of 0.3 K and experiences a photon noise NEP of 6×10^{-16} W $Hz^{-1/2}$. The 120 MΩ load resistors warm to 5.2 K by virtue of being inside the readout drawer with the 120 K JFETs.*

***Figure 4 (right):** Noise spectrum of prototype SHARC II bolometer. The 1/f noise is in reasonable agreement with an empirical model for the doped silicon thermistors[5].*

In order to facilitate scanning or nodding observing modes with slow optical modulations, the baseline SHARC II amplifier is an AC-biased "total power" readout[3,4]. To achieve the requisite detector stability, the SHARC II bolometer thermistors are doped over nearly the full 1 mm square pixel. An example noise spectrum using the total power readout is shown in Figure 4. The amplifiers can also be used in a conventional DC-biased configuration with optical chopping by turning off the modulator and demodulator.

RECENT DARK, COLD MEASUREMENTS

The SHARC II array was tested cold for the first time the week beginning March 25. An aluminum cover was placed on top of the detector radiation shield (Figure 2). Only one readout drawer was available; the first 4 rows of the array were read with a JFET dissipation 1/3 of the amount required to read the full array. For this configuration, the thermal performance (Table 1) met the design goal.

Table 1: *Measured thermal performance of bolometer array, 4×32 readout (30 mW dissipation)*

	4.2K LHe bath	**1.5K LHe bath**
Temperature of ^{3}He fridge	354 mK	299 mK
Temperature of detector	367 mK	307 mK
Temperature of JFET board	123 K	123 K
Temperature of readout box	4.8 K	2.8 K
Temperature of load resistors	6.3 K	5.2 K
Heat load from detector on ^{3}He fridge	4 μW	2 μW

The measured electrical properties of the first row of bolometers are reported in Table 2 and Figure 5. The observed NEP of 5×10^{-17} W Hz$^{-1/2}$ agrees with the prediction for a bolometer with no radiation load.

Table 2: *Measured electrical characteristics of typical bolometer in row 1 of SHARC II array (dark)*

Resistance R(T)	550 Ω exp[(45.1 K/T)$^{1/2}$] ; R(0.5 K) = 7.0 MΩ
Thermal conductance G(T)	1.5 nW/K $T^{1.9}$; G(0.5 K) = 0.40 nW/K
NEP(electrical)	5×10^{-17} W Hz$^{-1/2}$ (dark)
Responsivity S	4×10^{8} V/W (dark)
Time constant τ_e	6 msec
Heat capacity C(0.5 K)	4 pJ/K

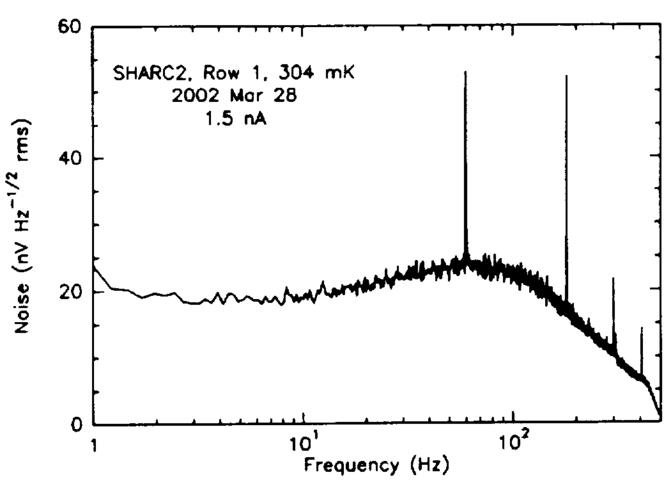


Figure 5: *Median noise spectrum for row 1 of SHARC II array during dark test. A DC bias was applied. In the 1-10 Hz signal band, the NEP is 5×10^{-17} W Hz$^{-1/2}$. The rise in noise toward ~80 Hz is caused by the increase in bolometer dynamic impedance Z(ω). The rolloff in noise at higher frequencies is caused by filtering in the amplifier and A/D system. Although 60 Hz harmonics are visible, the remainder of the spectrum is free from discrete features due to, for example, microphonics.*

SHARC II CAMERA

The SHARC II instrument was tested with a small array of pop-up bolometers ("SHARC 1.5") at the CSO in September 2000 (Figure 6). The camera had a high quantum efficiency and demonstrated the suitable imaging characteristics of the bare bolometer arrays for submillimeter astronomy. Our current plan is to commission the 12×32 SHARC II array during the remaining months of 2002 and to offer the instrument as an observatory facility in 2003. (See Table 3.)

Table 3: *SHARC II instrument characteristics*

array format	12×32 (1 mm)^2 bolometers
pixel scale	4.6″ (0.65 λ/D)
bandpass	350 μm ± 25 μm (HWHM)
resolution	8″ FWHM
field of view	2.5′ × 0.9′
NEFD (predicted, best 25% of winter nights, 1.3 airmasses)	≤1 Jy s$^{1/2}$

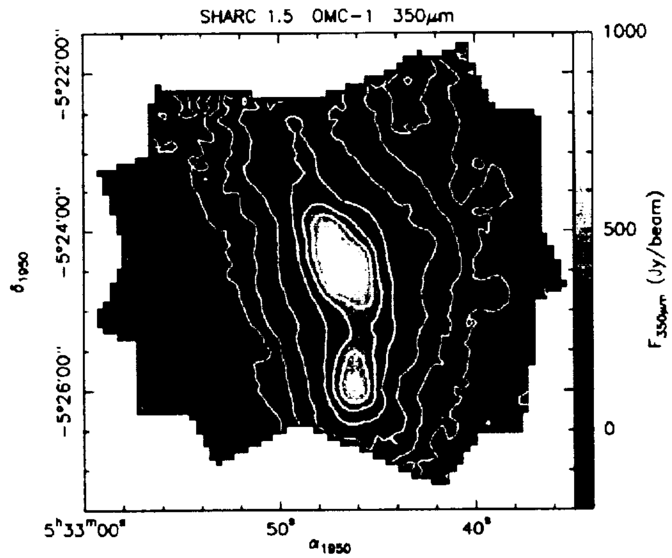


Figure 6: *Image of the Orion Nebula obtained with a 13-element prototype bolometer array in September 2000. The observing method employed conventional optical chopping and DC-biased bolometers.*

The following people contributed to the research reported in this paper: D. Benford, W. Collins, B. Derro, M. Gardner, A. Kovacs, D. Lis, P. Nelson, F. Peters, D. Sandford, C. Sappington, J. Staguhn, W. Smith, D. Warden, and H. Yoshida. The CSO is funded by the NSF through contract AST-9980846.

REFERENCES

1. D. A. Harper, et al. 2000, in Proceedings of SPIE, Vol. 4014, Airborne Telescope Systems, ed. R. K. Melugin & H. Roser
2. S. H. Moseley, C. D. Dowell, C. Allen, & T. G. Phillips. 2000, ASP Conf. Ser. 217, Imaging at Radio through Submillimeter Wavelengths, ed. J. G. Mangum & S. J. E. Radford
3. Wilbanks, T., Devlin, M., Lange, A. E., Sato, S., Beeman, J. W., & Haller, E. E. 1990, IEEE Trans. Nuclear Sci., 37, 566
4. Crill, B., et al. 2002, in preparation
5. Han, S.-I., et al. 1998, in Proceedings of SPIE, Vol. 3445, EUV, X-Ray, and Gamma Ray Instrumentation for Astronomy IX, ed. O. Siegmund & M. Gummin

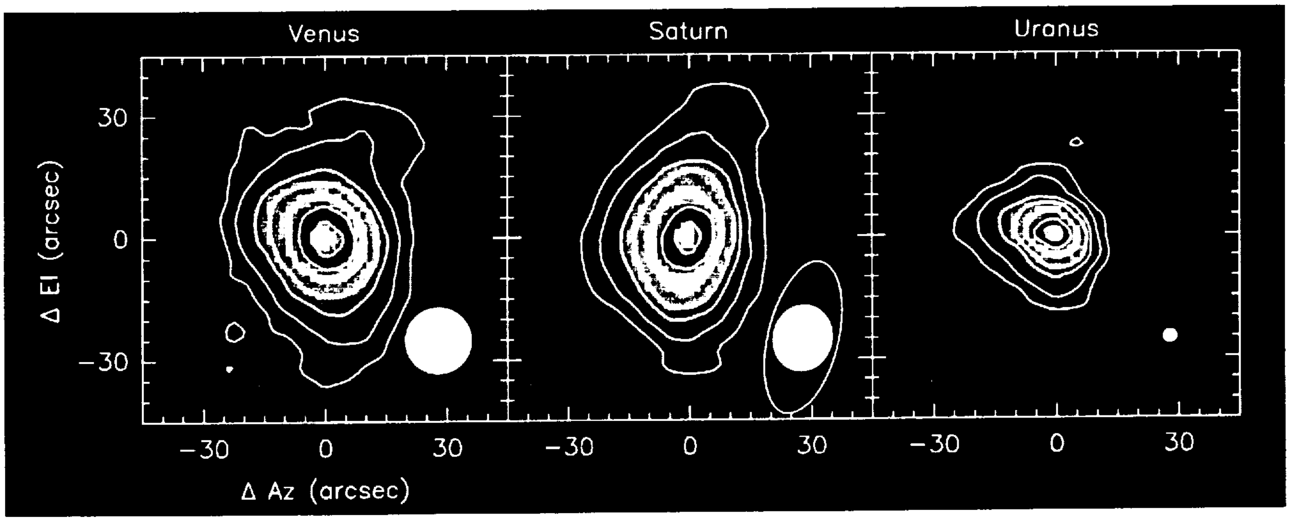


Figure 11. SHARC II 350 μm images of planets from July 2002. The contour intervals are 90%, 70%, 50%, 30%, 20%, 10%, and 5%. The disks at lower right show the physical extent of the planets at the time of observation. Venus was observed at 2.1 airmasses, Saturn at 1.7 airmasses, and Uranus at 1.5 airmasses.

ACKNOWLEDGMENTS

The CSO is funded by NSF grant AST 9980846. A large number of people at Goddard, Caltech, and elsewhere have contributed to the development of SHARC II, including: T. Ames, A. Bartels, D. Benford, W. Collins, B. Derro, J. Dotson, J. Foster, M. Gould, D. A. Harper, J. Higinbotham, Johns Hopkins Applied Physics Lab, K. Lewis, S. Lin, P. Nelson, R. Paniagua, F. Peters, V. Ponce, D. Sandford, C. Sappington, J. Staguhn, D. Warden, and J. Wirth.

REFERENCES

1. N. Wang, T. R. Hunter, D. J. Benford, E. Serabyn, D. C. Lis, T. G. Phillips, S. H. Moseley, K. Boyce, A. Szymkowiak, C. Allen, B. Mott, and J. Gygax, "Characterization of a submillimeter high-angular-resolution camera with a monolithic silicon bolometer array for the Caltech Submillimeter Observatory," *Appl. Opt.* **35**, pp. 6629–6640, 1996.
2. W. S. Holland, E. I. Robson, W. K. Gear, C. R. Cunningham, J. F. Lightfoot, T. Jenness, R. J. Ivison, J. A. Stevens, P. A. R. Ade, M. J. Griffin, W. D. Duncan, J. A. Murphy, and D. A. Naylor, "SCUBA: a common-user submillimetre camera operating on the James Clerk Maxwell Telescope," *Mon. Not. R. Astron. Soc.* **303**, pp. 659–672, 1999.
3. E. Kreysa, H. Gemünd, J. Gromke, C. G. Haslam, L. Reichertz, E. E. Haller, J. W. Beeman, V. Hansen, A. Sievers, and R. Zylka, "Bolometer array development at the Max-Planck-Institut für Radioastronomie," in *Advanced Technology MMW, Radio, and Terahertz Telescopes*, T. G. Phillips, ed., *Proc. SPIE* **3357**, pp. 319–325, 1998.
4. A. Omont, P. Cox, F. Bertoldi, R. G. McMahon, C. Carilli, and K. G. Isaak, "A 1.2 mm MAMBO/IRAM-30 m survey of dust emission from the highest redshift PSS quasars," *Astron. Astrophys.* **374**, pp. 371–381, 2001.
5. F. Piacentini, P. A. R. Ade, R. S. Bhatia, J. J. Bock, A. Boscaleri, P. Cardoni, B. P. Crill, P. de Bernardis, H. Del Castillo, G. De Troia, P. Farese, M. Giacometti, E. F. Hivon, V. V. Hristov, A. Iacoangeli, A. E. Lange, S. Masi, P. D. Mauskopf, L. Miglio, C. B. Netterfield, P. Palangio, E. Pascale, A. Raccanelli, S. Rao, G. Romeo, J. Ruhl, and F. Scaramuzzi, "The BOOMERANG North America Instrument: A Balloon-borne Bolometric Radiometer Optimized for Measurements of Cosmic Background Radiation Anisotropies from 0.3 degree to 4 degrees," *Astrophys. Jnl. Suppl.* **138**, pp. 315–336, 2002.

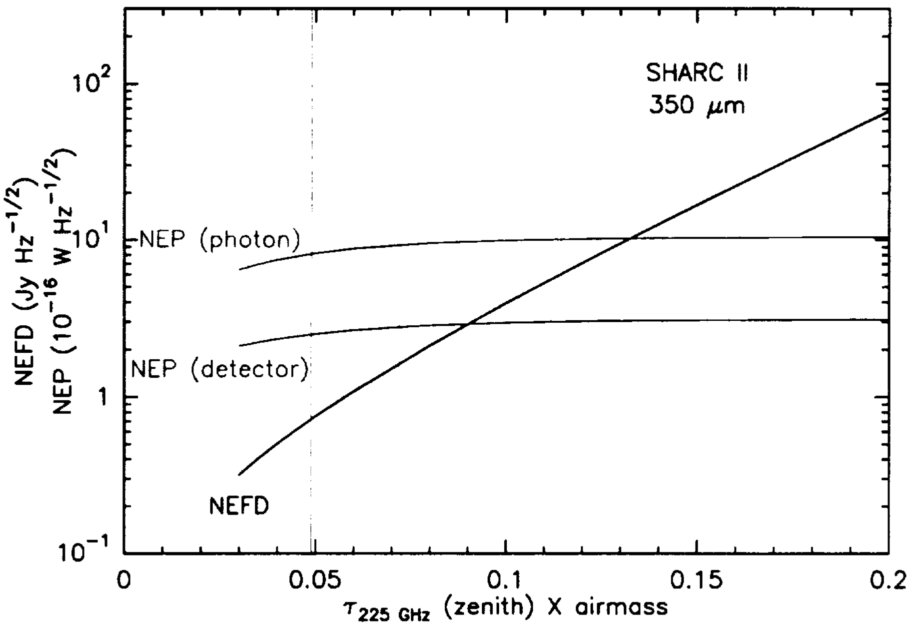


Figure 9. Photon-noise NEP, detector NEP, and background-limited NEFD as a function of atmospheric opacity. The photon NEP is fairly constant over the range of atmospheric conditions so that the slope of the NEFD is dominated by the atmospheric extinction $\tau(350\ \mu m) \approx 25\ \tau_{225GHz}$. The detector NEP (which includes the 7×10^{-17} W Hz$^{-1/2}$ from internal radiation; §7.1) is approximately one third of the photon NEP, meaning that it inflates the system noise by only ~5%. The vertical lines show the quartiles of the Mauna Kea atmospheric opacity distribution for winter nights.

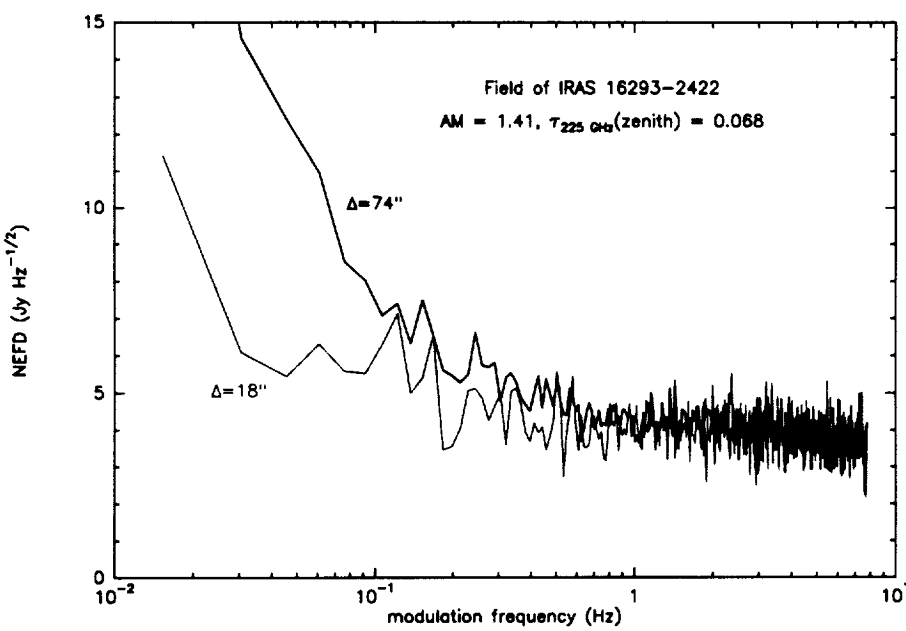


Figure 10. Observed NEFD for SHARC II at 350 μm for a scanned observing mode without chopping. The 1/f noise is lower for pixels separated by 18″ (bottom trace) than it is for pixels separated by 74″ (top trace), which we attribute to variable gradients in sky emission.

6. A. T. Lee, P. Ade, A. Balbi, J. Bock, J. Borrill, A. Boscaleri, B. P. Crill, P. de Bernardis, H. del Castillo, P. Ferreira, K. Ganga, S. Hanany, V. Hristov, A. H. Jaffe, A. E. Lange, P. Mauskopf, C. B. Netterfield, S. Oh, E. Pascale, B. Rabii, P. L. Richards, J. Ruhl, G. F. Smoot, and C. D. Winant, "MAXIMA: An Experiment to Measure Temperature Anisotropy in the Cosmic Microwave Background," in *3K Cosmology, AIP Conf. Proc.* **476**, pp. 224+, 1999.
7. D. A. Harper, C. A. Allen, M. J. Amato, T. Ames, A. Bartels, S. C. Casey, R. J. Derro, R. Evans, I. Gatley, S. J. Heimsath, A. Hermida, M. D. Jhabvala, J. H. Kastner, R. F. Loewenstein, S. H. Moseley, R. J. Pernic, T. Rennick, H. E. Rhody, D. Sandford, R. A. Shafer, P. J. Shirron, G. Voellmer, S. Wang, and J. Wirth, "HAWC: a far-infrared camera for SOFIA," in *Airborne Telescope Systems*, R. K. Melugin and H.-P. Roeser, eds., *Proc. SPIE* **4014**, pp. 43–53, 2000.
8. M. J. Griffin, J. J. Bock, and W. K. Gear, "The Relative Performance of Filled and Feedhorn-Coupled Focal-plane Architectures," *Appl. Opt.* , accepted, 2002.
9. G. Voellmer, C. A. Allen, M. J. Amato, A. E. Bartels, D. J. Benford, R. J. Derro, C. D. Dowell, D. A. Harper, S. H. Moseley, Jr., P. J. Shirron, W. W. Smith, and J. G. Staguhn, "Design and fabrication of two-dimensional semiconducting bolometer arrays for HAWC and SHARC-II," in *Millimeter and Submillimeter Detectors for Astronomy*, T. G. Phillips and J. Zmuidzinas, eds., *Proc. SPIE* **4855**, 2002.
10. S.-I. Han, R. Almy, E. Apodaca, W. Bergmann, S. Deiker, A. Lesser, D. McCammon, K. Rawlins, R. L. Kelley, S. H. Moseley, F. S. Porter, C. K. Stahle, and A. E. Szymkowiak, "Intrinsic 1/f noise in doped silicon thermistors for cryogenic calorimeters," in *EUV, X-Ray, and Gamma-Ray Instrumentation for Astronomy IX*, O. H. Siegmund and M. H. Gummin, eds., *Proc. SPIE* **3445**, pp. 640–644, 1998.
11. S. H. Moseley, Jr., C. D. Dowell, C. Allen, and T. G. Phillips, "Semiconducting Pop-Up Bolometers for Far-Infrared and Submillimeter Astronomy," in *Imaging at Radio through Submillimeter Wavelengths*, J. G. Mangum and S. J. E. Radford, eds., *ASP Conf. Ser.* **217**, pp. 140–149, 2000.
12. M. M. Freund, R. F. Silverberg, V. Ponce, C. A. Allen, C. Sappington, S. H. Moseley, Jr., D. A. Harper, Jr., R. F. Loewenstein, and C. D. Dowell, "Testing and performance results for the 12×32 SHARC II and HAWC bolometer arrays," in *Millimeter and Submillimeter Detectors for Astronomy*, T. G. Phillips and J. Zmuidzinas, eds., *Proc. SPIE* **4855**, 2002.
13. C. D. Dowell, J. E. Groseth, T. G. Phillips, C. A. Allen, S. R. Babu, M. D. Jhabvala, S. H. Moseley, Jr., and G. M. Voellmer, "The 12×32 pop-up bolometer array for the SHARC II camera," in *Far-IR, Sub-MM & MM Detector Technology Workshop*, J. Wolf, J. Farhoomand, and C. R. McCreight, eds., *NASA* **CP-211408**, 2002.
14. M. Jhabvala, S. Babu, C. Monroy, M. M. Freund, and C. D. Dowell, "Development of low-noise high value chromium silicide resistors for cryogenic detector applications," *Cryogenics* , accepted, 2002.
15. G. Dall'Oglio, W. Fischer, L. Martinis, and L. Pizzo, "Improved ^{3}He/^{4}He refrigerator," *Cryogenics* **33**, pp. 213–214, 1993.
16. E. Serabyn, "Wide-field Imaging Optics for Submm Arrays," in *Multi-Feed Systems for Radio Telescopes*, D. T. Emerson and J. M. Payne, eds., *ASP Conf. Ser.* **75**, pp. 74–81, 1995.
17. T. R. Hunter, D. J. Benford, and E. Serabyn, "Optical Design of the Submillimeter High Angular Resolution Camera (SHARC)," *Pub. Astron. Soc. Pac.* **108**, pp. 1042–1050, 1996.
18. J. R. Pardo, J. Cernicharo, and E. Serabyn, "Atmospheric Transmission at Microwaves (ATM): An Improved Model for mm/submm applications," *IEEE Trans. on Antennas and Propagation* **49**, pp. 1683–1694, 2001.
19. L. A. Reichertz, B. Weferling, W. Esch, and E. Kreysa, "The fastscanning observing technique for millimeter and submillimeter astronomy," *Astron. Astrophys.* **379**, pp. 735–739, 2001.
20. G. Sandell, "Secondary calibrators at submillimeter wavelengths.," *Mon. Not. R. Astron. Soc.* **271**, pp. 75–80, 1994.
21. T. J. Ames and L. Case, "Distributed framework for dynamic telescope and instrument control," in *Advanced Telescope and Instrumentation Control Software II*, H. Lewis, ed., *Proc. SPIE* **4848**, 2002.
22. J. C. Mather, "Bolometer noise: nonequilibrium theory," *Appl. Opt.* **21**, pp. 1125–1129, 1982.
23. G. H. Rieke, *Detection of Light: from the Ultraviolet to the Submillimeter*, Cambridge University Press, Cambridge, 1994.